



# Earth Science Technology Program (ESTP)

## ESE Roadmaps

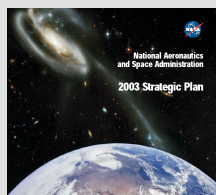
February 25, 2003

Rudy Richter  
301-286-7652

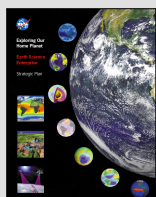


# From Strategic Planning to Implementation

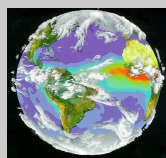
## Agency Strategic Plan



## ESE Strategic Plan



## Research Strategy



## Education Strategy



## Technology Strategy



## Science Questions

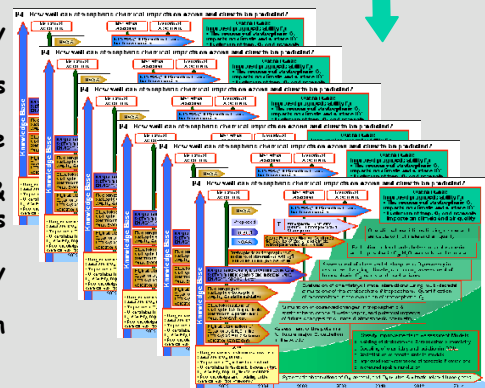
### Science Questions from the Research Strategy

Variability	Forcing	Response	Consequence	Prediction
V1: Precipitation, evaporation & cycling of water changing?	F1: Atmospheric constituents & solar radiation on climate?	R1: Clouds & surface hydrological processes on climate?	C1: Weather variation related to climate variation?	P1: Weather forecasting improvement?
V2: Global ocean circulation varying?	F2: Changes in land cover & land use?	R2: Ecosystem responses & effects on global carbon cycle?	C2: Consequences in land cover & land use?	P2: Transient climate variations?
V3: Global ecosystems changing?	F3: Surface transformation?	R3: Changes in global ocean circulation?	C3: Coastal region changes?	P3: Trends in long term climate?
V4: Stratospheric ozone changing?	F4: Stratospheric trace constituent responses?	R4: Stratospheric trace constituent responses?	C4: Future stratospheric chemical impacts?	P4: Future stratospheric chemical impacts?
V5: Ice cover mass changing?	F5: Sea level affected by climate change?	R5: Sea level affected by climate change?	C5: Future concentrations of carbon dioxide and methane?	P5: Future concentrations of carbon dioxide and methane?
V6: Motions of Earth & interior processes?	F6: Pollution effects?	R6: Pollution effects?		

■ Requires both systematic & exploratory satellites  
■ Requires systematic satellite observations  
■ Requires exploratory satellite observations  
■ Requires pre-operational and/or systematic ops  
■ Use available/new observations in better models

## Six Focus Area Roadmaps

Atmospheric Chemistry  
 Weather Dynamics  
 Ocean, Ice and Climate  
 Carbon Cycle & Ecosystems  
 Water and Energy  
 Solid Earth



## Implementation

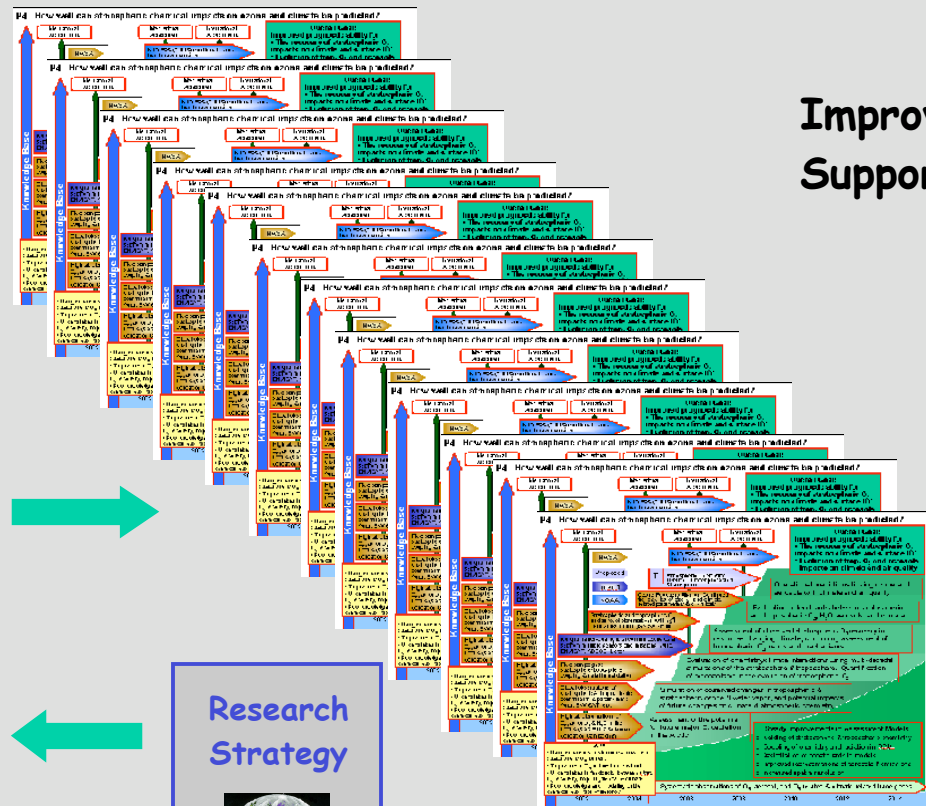
- The Earth Science program is linked to the NASA Strategic Plan
- The 23 science questions from the Research Strategy are managed under 6 focus areas
- Roadmaps dictate how the focus areas answer the science questions by defining measurements and research outcomes.

# From Strategic Planning to Implementation

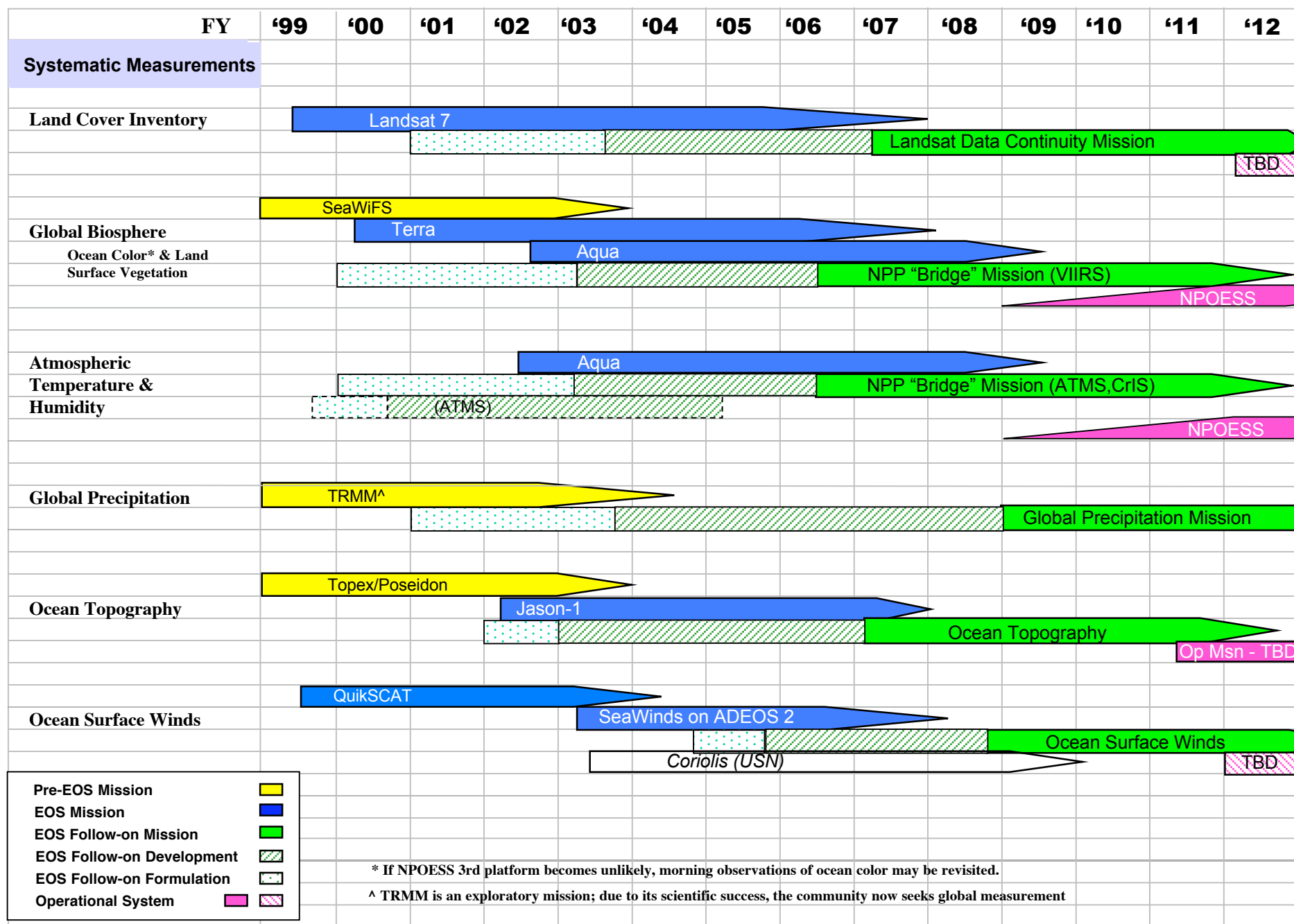
12 National Applications Roadmaps

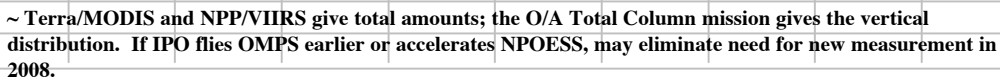
Improving National Decision Support Systems in:

Aviation Safety  
Carbon Management  
Energy Forecasting  
Public Health  
Homeland Security  
Disaster Preparedness  
Coastal Management  
Water Management  
Invasive Species  
Community Growth  
Agricultural  
Air Quality



Implementation is based on creating benchmarking capability and measurable enhancements for National decision support systems



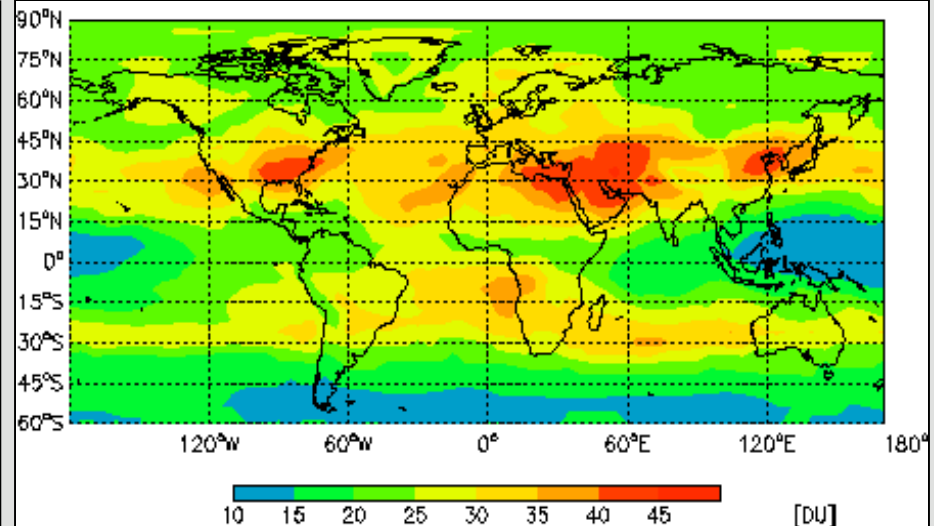




# Understanding the Trace Constituent and Particulate Composition of the Earth's Atmosphere and Predicting its Future Evolution

## *Background and Issues:*

- The atmosphere is a “fast integrator” for the Earth, transporting surface emissions quickly around the world (~ week), between hemispheres (~ year), and to high altitudes (~ 3-5 years to 50 km)
- Human activity is significantly changing atmospheric composition in ways that can affect the global, regional, and local environment
- Key Environmental Issues:
  - Global Ozone Depletion and its Impact on Surface UV Radiation
  - Climate Forcing by Radiatively Active Gases and Aerosols
  - Global Air Quality



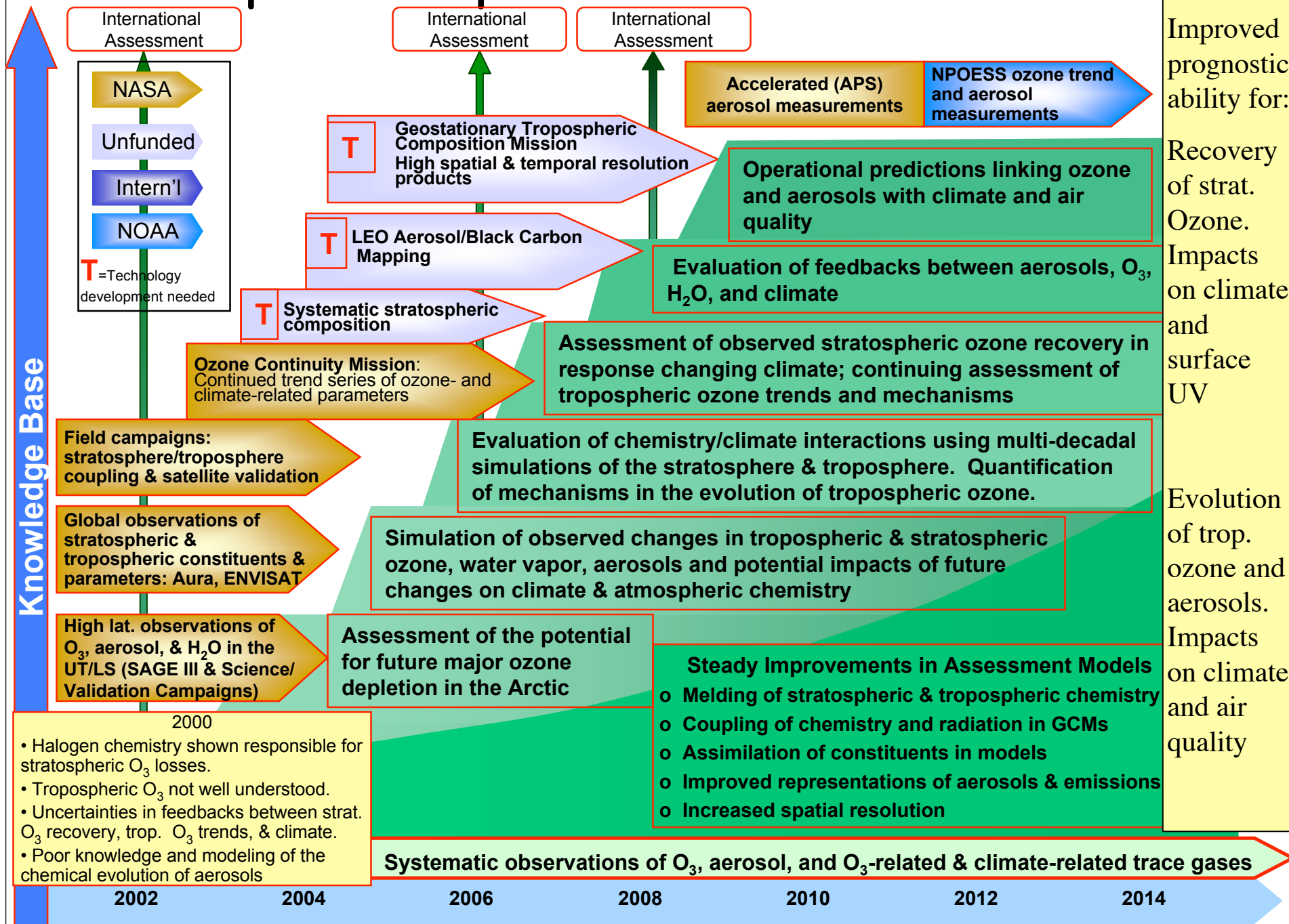
## *Enhanced Ozone and Aerosols*

Global model simulation of tropospheric ozone columns

## *Why NASA?*

- Global Observations of Ozone, Aerosols, and Related Trace Gases
- Study of Atmospheric Processes Using Unique Airborne Platform - Sensor Suite Combinations
- Modeling and Data Assimilation to Provide Atmospheric Data Products and Forecasts
- Note:* NASA roles in Research and Monitoring are Called for under Federal Law (NASA Authorization Act, Clean Air Act)

# Atmospheric Composition





# Anticipated Progress in Answering the Questions:

## Where we are now

Halogen chemistry largely responsible for stratospheric O<sub>3</sub> loss, but exact % unknown

Connection between climate change and stratospheric O<sub>3</sub> chemistry recognized but effects on O<sub>3</sub> recovery not well understood

Radiatively important change in atmospheric water observed but the temporal variation is not quantitatively understood

Spatially varying trends in tropospheric O<sub>3</sub> observed but not understood

Tropospheric O<sub>3</sub> shown to be transported over long distances, but the contributions of such transported O<sub>3</sub> to regional budgets are not understood

Geographical and vertical distribution of atmospheric aerosols are identified but the evolution, composition and properties are not understood

## Where we plan to be

Quantitative components of O<sub>3</sub> loss (e.g., chemistry vs. dynamics) are understood

Integrated chemistry and climate models provide improved prognostic ability on the extent and timing of O<sub>3</sub> recovery

Observed changes in atmospheric water are understood and future changes can be predicted

Geographic evolution of tropospheric O<sub>3</sub> is quantified and understood

The extent of regional pollution that is attributable to the long-range transport of ozone is quantified

Aerosol evolution, composition, vertical distribution, and radiative impacts are quantified and this information is used in climate models

2002

~ 2015



# Anticipated Outcomes and Uses of Results

## Result / Capability

Global ozone time series, variability, and trends quantified at regional spatial resolution. Chemical sources and sinks identified and quantified. Chemistry-climate feedbacks quantified and assessed.

Quantification of black carbon/aerosol and greenhouse gas sources and sinks. Quantification of controlling processes and their interactions.

Global Air Quality: High temporal and spatial resolution composition measurements. Global climate change impacts on regional air quality and the influence of regional air quality on the global climate.

## Products / Uses for Decision Support

Quantitative global **monitoring & evaluation tools:** (coupled stratosphere/troposphere assessment models) to assess the efficacy of the Montreal Protocol on ozone recovery and to assess effects of climate change on ozone recovery and future atmospheric composition.

**Maps, data products and information** on relationships among them as input for decision support systems. Simulation models that enable “If ... , then...” scenarios to be explored.

**Climate Forecasts:** Projections of changes in carbon, chemical, and aerosol sources and sinks, due to combinations of real-world forcings of global environmental change with sub-regional specificity and good reliability for ~6 mos. to 2 years into the future; and for 50-100 years into the future for a variety of policy-relevant “if ... , then ...” scenarios

**Air Quality Forecasts:** Linkage of NWP models to air quality models for short-term and seasonal air quality forecasts. Assessment of feedbacks between regional air quality and global climate change.



# NASA Weather Research Roadmap



**Steps to help the nation  
achieve improvement in  
near-term forecasts using  
NASA's latest data and  
modeling research.**

**A Combined Vision of  
NASA, NOAA, and the Research  
Community**



# Weather Prediction

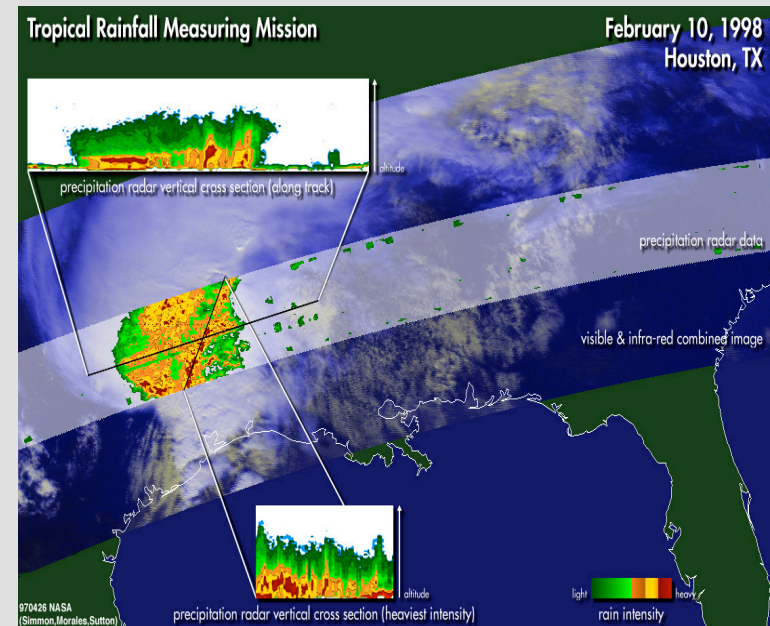
**How can improvements in weather prediction be realized? What are the most important needed investments in observations and modeling technologies and how can they best be transferred to operations?**

## Background and Issues:

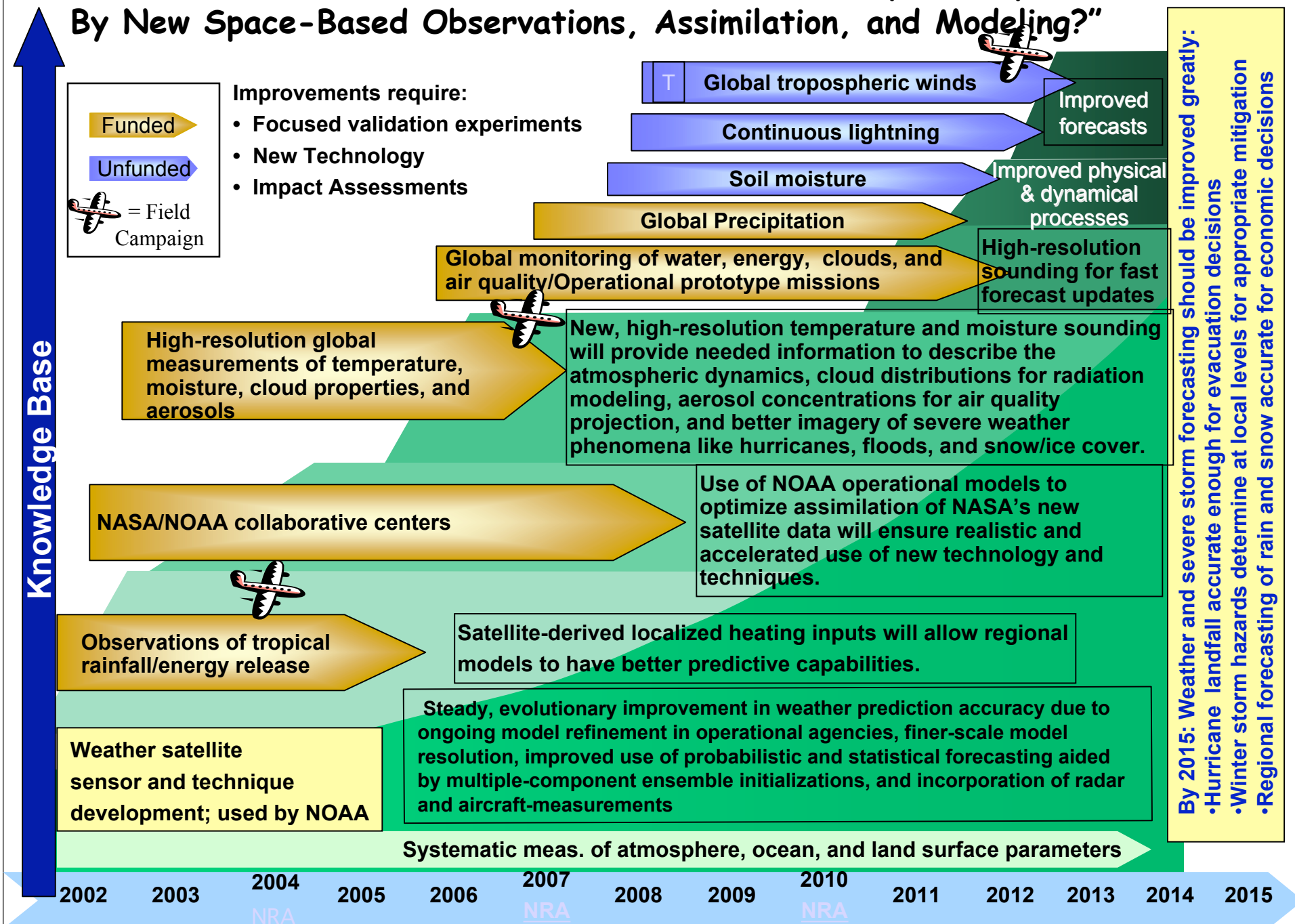
- Improvements in weather prediction have great social, economic value
- Goals are jointly worked with other agencies via USWRP and other interagency activities
- Better forecasts needed for hurricanes, severe thunderstorms and tornadoes, winter-time storms, and flash floods
- Improved and new measurements are needed to make the required progress

## Why NASA?

- NASA space-based measurements, numerical modeling, and data assimilation have already made great contribution
- Technology for new global (space-based) observations needed can only be developed and flight-proven by NASA
- NASA will need to continue leadership role in how to best use new space-based measurements in data assimilation/forecast systems
- NASA and other agencies will partner on the technology transfer



# "How Can Weather Forecast Duration and Reliability Be Improved By New Space-Based Observations, Assimilation, and Modeling?"





# National Weather Forecast Improvement Goals

## TODAY:

3-day forecast at 93%\*

7-day forecast at 62%\*

3-day >1" rainfall forecast, low skill

3-day severe local storm forecast with low-moderate confidence

Thunderstorm occurrence to \_ hr (within 25 nm)

Tornado lead time 10 min

Hurricane landfall

+/- 400 km at 2-3 days

Air quality day-by-day

## GOALS for 2010:

5-day forecast at >90%\*

7-10 day forecast at 75%\*

3-day rainfall forecast routine

7-day severe local storm forecast, mod. to occasional high confidence

Thunderstorm occurrence (convective initiation) to 3 hr

Tornado lead time 18 min

Hurricane landfall

+/- 100 km at 2-3 days

Air quality forecast at 2 days

\*Accuracy refers to sea-level pressure in N. Hemisphere winters



# Key Steps to Achieve NASA Weather Goals

- Coordinate enabling research with NOAA
- Establish priorities for Joint NASA/NOAA Centers
- Develop model assimilation techniques for new satellite data
- Conduct focused field measurements to improve model physics, dynamics and chemistry
- Test impacts of new data at Joint Centers
- Incorporate new data and techniques in operational forecasting
- Assess forecast improvements
- Refocus priorities for additional improved forecast accuracy



# Enabling Research for Improved Weather Forecasts

- Understanding operational needs of forecasters
- Accelerated assimilation of new satellite data
- Better numerical models of key processes
- Targeted field measurement efforts to quantify interactions
- Joint research and modeling to accelerate progress
- Linked computer models to account for system interactions
- New satellite data algorithms to compute accurate parameters
- Design and implementation of decision support systems



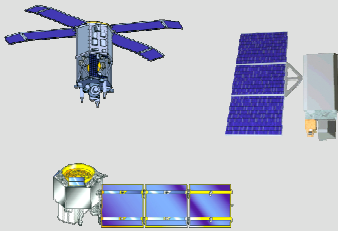
# Weather Program Implementation Plan and the ESE Research Strategy

- **VARIABILITY**: NASA and NOAA studies of weather regime occurrence for climatology and forecast verification
- **FORCING**: Solar and oceanic measurements provide time-variable boundary and initial conditions for numerical models
- **RESPONSE**: Sophisticated coupled atmospheric, boundary-layer, land/ocean surface, cloud micro-physics, and chemistry models enable forecasts of increasing time and space resolution with additional forecast elements such as air pollution regimes.
- **CONSEQUENCES**: Communications media and private meteorologists document the societal and economic consequences.
- **PREDICTION**: NOAA/NCEP is responsible ultimately for all of the weather/environmental predictions; NASA is assisting NOAA with accelerated assimilation of new satellite data and focused science measurement programs for understanding better the physical, dynamic, and chemical interactions.

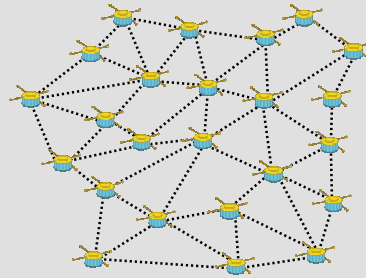


# NASA Helps Society Use Weather Satellite Data

## Advanced Satellite Sensors



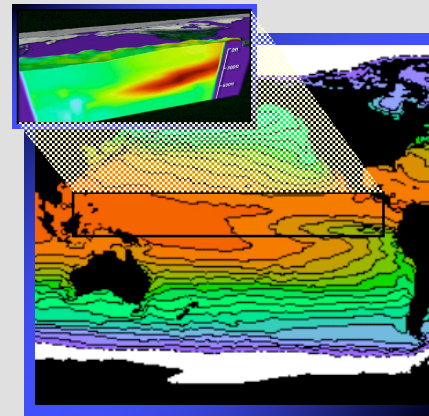
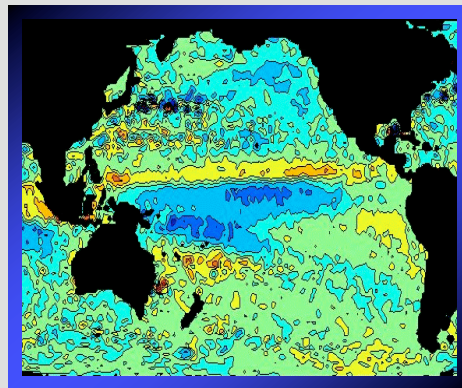
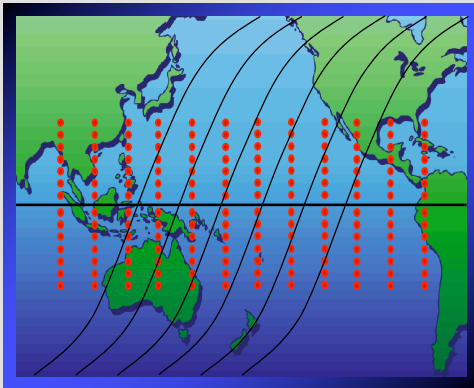
## Processing Webs



## Information Synthesis



## Access to Knowledge

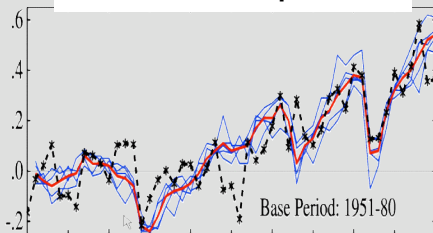


**Roadmap from Satellite Data to Decision Support Systems**

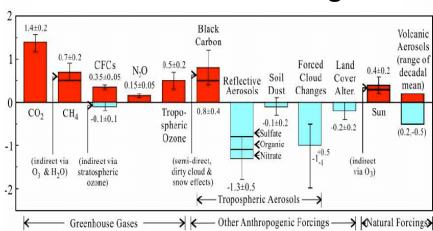


# Climate Variability and Change

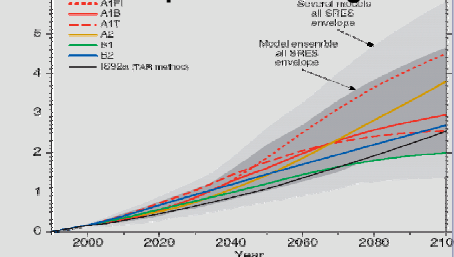
Surface Air Temperature



Global Climate Forcing

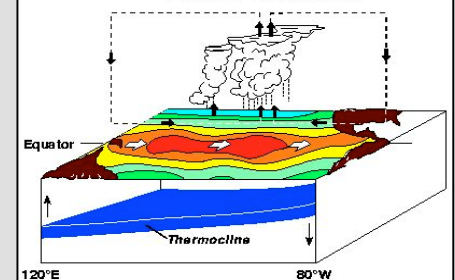


Temperature Change

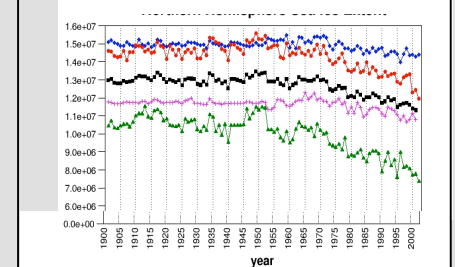


- How is global ocean circulation varying on interannual, decadal, and longer time scales?
- What changes are occurring in the mass of the Earth's ice cover?
- How can climate variations induce changes in the global ocean circulation?
- How is global sea level affected by natural variability and human-induced change in the Earth system?
- How can predictions of climate variability and change be improved?

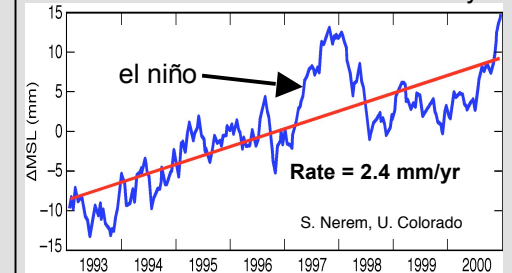
El Niño Conditions



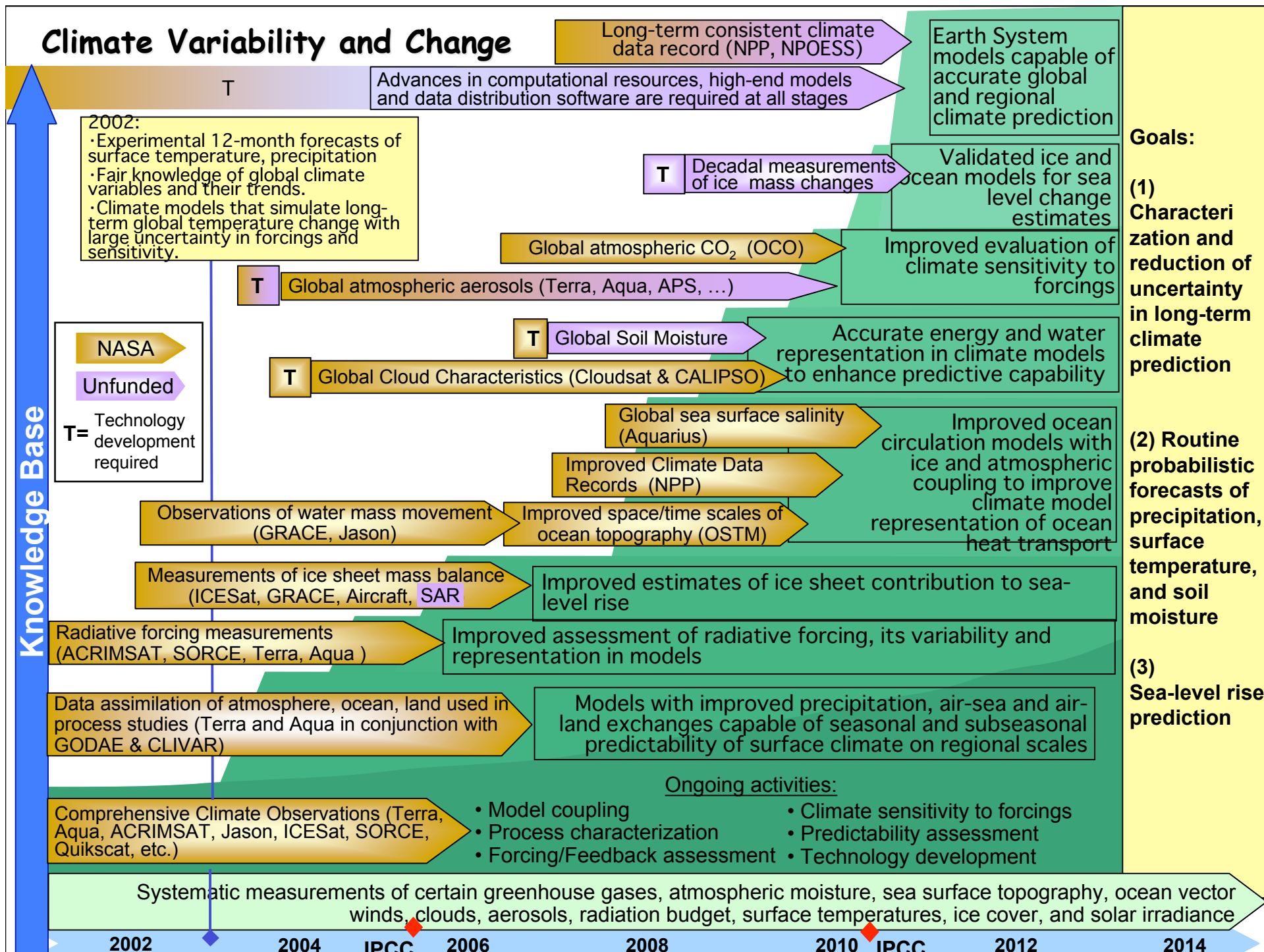
Sea Ice Extent



Global Mean Sea Level Anomaly



*Climate change is one of the major paradigms guiding Earth System Science today. NASA is at the forefront of quantifying forcings and feedbacks of recent and future climate change. Our comprehensive end-to-end program goes from global high-resolution observations to data assimilation and model predictions.*





# Anticipated Progress in Answering the Questions: Climate Variability and Change

## Where we are now

Large uncertainties in tropospheric aerosol forcing. Good knowledge of greenhouse gases and their corresponding forcing.

Climate models simulate long-term global temperature change with large uncertainty in forcings and sensitivity.

6-9 month forecasts of global surface temperatures and precipitation are conducted routinely

Insufficient knowledge and representation of processes such as upwelling and surface heat, freshwater and the modeling of low level clouds

Limited knowledge of partitioning of sea level rise including uncertainty of whether ice sheets are growing or shrinking

## Where we plan to be

Precise knowledge of greenhouse gases forcings and feedbacks (sea ice, water vapor etc.). Good knowledge of tropospheric aerosol forcing and cloud effects.

Comprehensive earth system models capable of simulating future climate changes based on different forcing scenarios with good confidence.

Routine operational integrated modeling and forecasting system for seasonal-to-interannual predictions using multiple satellite and *in situ* data streams.

Enhanced global satellite observations of surface winds, heat, freshwater, radiation and vertical distribution of clouds and temperature to improve modeling of air-sea exchange and low-level clouds

Decadal ice sheet mass balance estimates, improved assessment of contributions from glaciers and ocean thermal expansion with greatly enhanced sea level prediction capabilities

2002

~ 2015



# Anticipated Outcomes and Uses of Climate Models: Predicting Future Climate Variability and Change

## Model Capability

Comprehensive earth system models capable of simulating future climate changes based on different forcing scenarios with good confidence.

Integrated modeling and forecasting system for seasonal-to-interannual predictions using multiple satellite and *in situ* data streams.

Climate models that:

- Reliably characterize regional effects of global climate change
- Provide quantitative evaluation of climate sensitivity
- Provide sources of prediction skill globally

Regional sea level rise prediction capability

## Products / Uses for Decision Support

Quantitative options for reducing climate forcings provided to policy and management decision makers.

Forecasts of risk of extreme events or prolonged wet or dry conditions.

Projections of changes in the climate system with sub-regional specificity and good reliability.

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Credible, useful analyses of climate forcings and feedbacks for a variety of policy-relevant “what if” scenarios.

Information for coastal planning and management

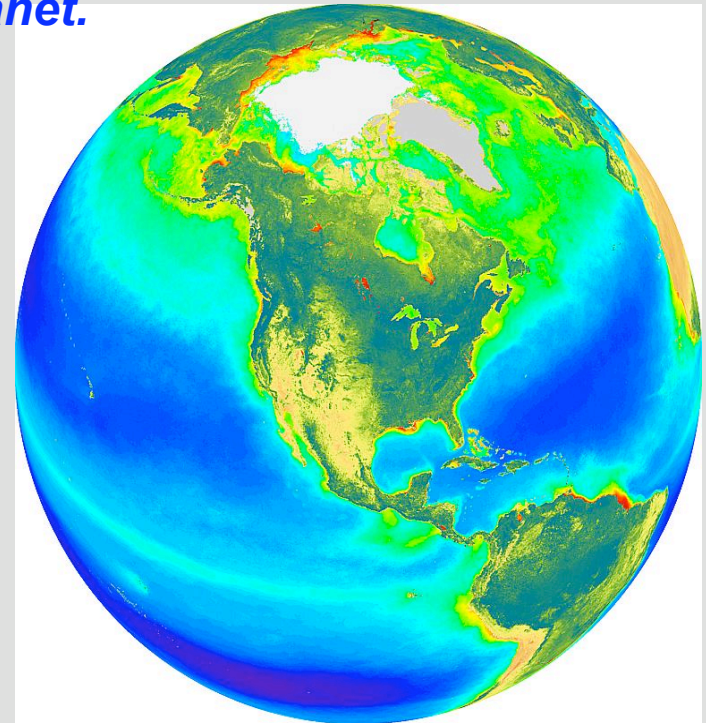


# Carbon, Ecosystems, and Biogeochemistry

Knowledge of the interactions of global biogeochemical cycles and terrestrial and marine ecosystems with global environmental change and their implications for the Earth's climate, productivity, and natural resources is needed *to understand and protect our home planet.*

## Important Concerns:

- Potential greenhouse warming ( $\text{CO}_2$ ,  $\text{CH}_4$ ) and ecosystem interactions with climate
- Carbon management (e.g., capacity of plants, soils, and the ocean to sequester carbon)
- Productivity of ecosystems (food, fiber, fuel)
- Ecosystem health and the sustainability of ecosystem goods and services
- Biodiversity and invasive species



NASA provides the global perspective and unique combination of interdisciplinary science, state-of-the-art Earth system modeling, and diverse synoptic observations needed to document, understand, and project carbon cycle dynamics and changes in terrestrial and marine ecosystems and land cover.



# Overall Strategy for NASA Carbon, Ecosystems, and Biogeochemistry Research

- Continue the synoptic global time series **observations of ocean color, vegetation properties, and land cover (systematic measurements)**
- Validate remote sensing observations and improve process understanding through **field and oceanographic campaigns and case studies of land use change**
- Develop **Earth system models**: biospheric models, interactive land-ocean-atmosphere coupling, model-data fusion, carbon data assimilation, linked socio-economic and biophysical models (e.g., human-ecosystems-climate models )
- Implement **new, global observations of key missing variables** (exploratory and demonstration measurements)
- Evaluate model performance, compare model projections with data, quantify errors and uncertainties in order to provide credible, tested, **ecological forecasts and improved climate change projections**



# Carbon, Ecosystems, and Biogeochemistry

## Desired Outcomes:

- Scientific assessments of specific ecosystem responses to potential environmental changes
- Quantitative carbon budgets and emissions estimates for key global ecosystems
- Fundamental understanding of primary productivity and the consequences of land cover and land use change as a basis for applications to agriculture, forestry, fisheries, sustainable land and marine resource management, carbon management, and biodiversity conservation
- Information on ecosystem interactions with and feedbacks to the atmosphere that can be used to improve weather and climate prediction and to assess impacts on atmospheric chemistry



# Carbon, Ecosystems, and Biogeochemistry: Key for Linkages



Water and Energy



Atmospheric Composition



Weather

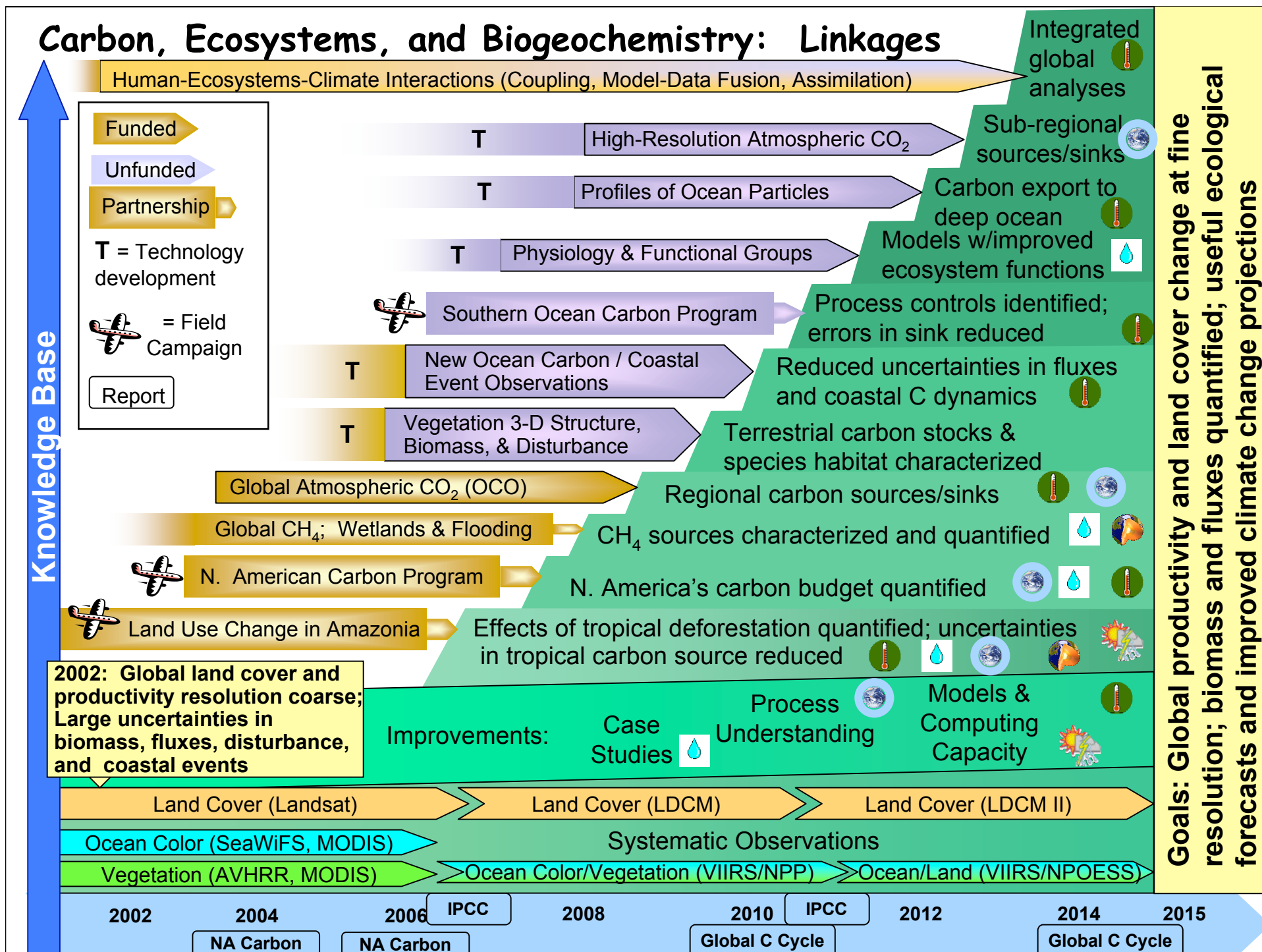


Climate, Oceans and Ice



Earth's Surface and Interior

# Carbon, Ecosystems, and Biogeochemistry: Linkages





# Anticipated Progress in Answering the Questions:

## Where we are now

Global primary productivity and land cover time series available at coarse (~8 km resolution); only short time periods and certain regions at higher resolutions.

Available observations (*in situ*) of global CO<sub>2</sub>, biomass, plant community vertical structure, and species functional groups insufficient to resolve many issues.

Large uncertainties in N. Hemisphere terrestrial carbon storage, ocean uptake and storage, and tropical land use effects. Global carbon budget not balanced.

Ecosystem and biogeochemical cycling models resolve only very large year-to-year variations; multiple controlling processes not well quantified or modeled.

## Where we plan to be

Decadal variability in global productivity quantified at moderate (~1 km) resolution; Periodic global land cover change analyzed at fine (~30 m) resolution.

New observations (space-based) enable quantification of carbon and nutrient storage and fluxes, disturbance and recovery processes, and ecosystem health.

Carbon sources and sinks identified and quantified at sub-regional scales (~100 km), with small errors. Global carbon budget balanced on annual basis.

Earth system models able to correctly portray most interannual variations and the multiple, interacting processes that control them, with sub-regional specificity.

2002

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# Anticipated Outcomes and Uses of Results

## Result / Capability

Global primary productivity and land cover change time series variability and trends quantified at moderate to fine spatial resolution. Carbon sources and sinks identified and quantified.

Quantification of carbon and nutrient storage and fluxes, disturbance and recovery processes, and ecosystem health. Quantification of controlling processes and their interactions.

Models that:

- achieve carbon balance
- reliably characterize interannual variability and sub-regional processes
- quantitatively portray multiple, interacting controlling

processes - are able to correctly simulate past land cover, ecosystem dynamics and biogeochemical cycling

## Products / Uses for Decision Support

Quantitative global **monitoring & evaluation tools**: to assess the efficacy of **carbon management** (e.g. sequestration in biomass); to assess agricultural, forest, and fisheries **productivity**; to **verify emissions and/or sequestration reporting** by nations/sectors.

**Maps, data products and information** on relationships among them as **input for decision support systems**. Simulation models that enable “If ... , then...” scenarios to be explored.

**Ecological Forecasts**: Projections of changes in carbon sources and sinks, land cover, and ecosystem dynamics due to combinations of real-world forcings of global environmental change with sub-regional specificity and good reliability for ~6 mos. to 2 years into the future (e.g., harmful algal blooms, invasive species).

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**Inputs for Climate Projections**: Credible, useful projections of future climate change (including improved ecosystem feedbacks and projections of CO<sub>2</sub> and CH<sub>4</sub> concentrations) for 50-100 years into the future for a variety of policy-relevant “if ... , then ...” scenarios.



# Carbon, Ecosystems, and Biogeochemistry: Anticipated Products

## Maps & Data Products

- 2006: N. America's land cover change quantified, 1990-2005
- 2007: Global wetland extent
- 2008: Monthly maps of net fluxes of CO<sub>2</sub> and CH<sub>4</sub>
- 2008: Vegetation structure & biomass for N. America
- 2011: Global land cover change quantified, 1990-2005
- 2012: Global gridded canopy height and biomass maps
- 2012: Global disturbance & recovery for terrestrial ecosystems
- 2015: Global forest age & regrowth stage maps

## Monitoring & Evaluation

- 2004: Global annual primary productivity estimates
- 2005: Quantification of interannual variability in productivity (marine from 1997; terrestrial from 2001)
- 2008: Quantitative attribution of CO<sub>2</sub> and CH<sub>4</sub> fluxes to sources
- 2008: Interannual time series of air-sea flux of CO<sub>2</sub>
- 2012: Monthly analyses of key ecosystem states and carbon fluxes at native resolution of satellite imagery
- 2014: Mixed layer particulate carbon concentration estimates

## Forecasts & Projections

- 2012: Global and regional ecosystem/biogeochemical/carbon models with reduced uncertainties due to spatial distribution and extent of ecosystems and environmental properties
- 2013: Improved understanding of the processes controlling variability in ocean productivity
- 2014: Fully coupled Earth system model forecasting of interannual variability in ecosystem processes and carbon fluxes that will be evaluated, leading to credible, tested models of future climate and ecosystem change.



# Global Water Cycle

The global water cycle is resolved at only coarse resolutions, hampering climate models' ability to recreate hydrologic means and extremes that are relevant to local scales. Uncertainties in basic hydrological processes and in the strength of feedback processes, such as clouds and cloud processes, coupling of sea-ice-land, air-sea, and land surface effects result in large ranges in predictions of impacts to the overall climate system.

## Water Cycle Study requires:

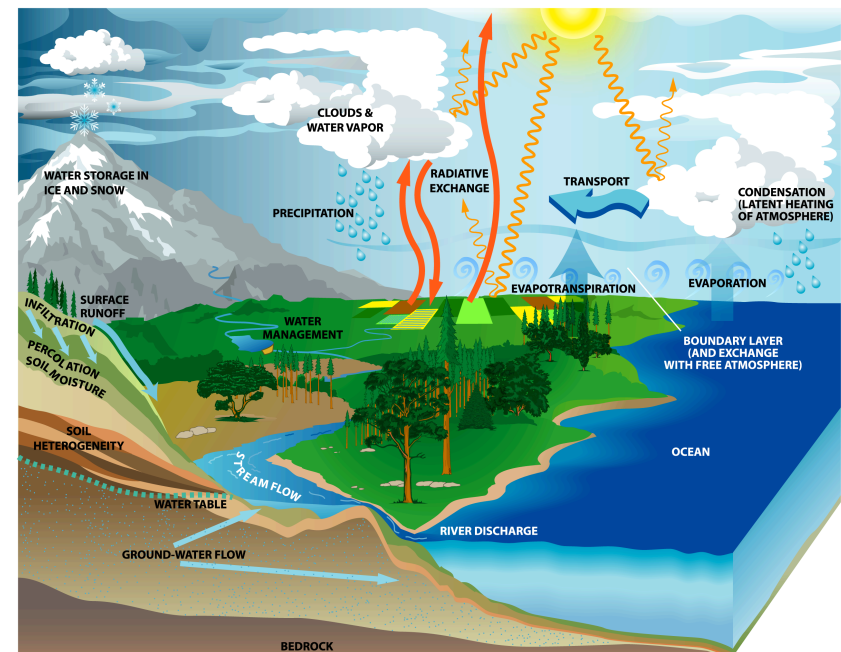
Land-atm and ocean-atm interactions-  
partitioning of water and energy

Hydrologic states and fluxes: clouds, soil  
moisture, snow, precipitation, evaporation, etc.

**Understanding the water cycle is important  
for:**

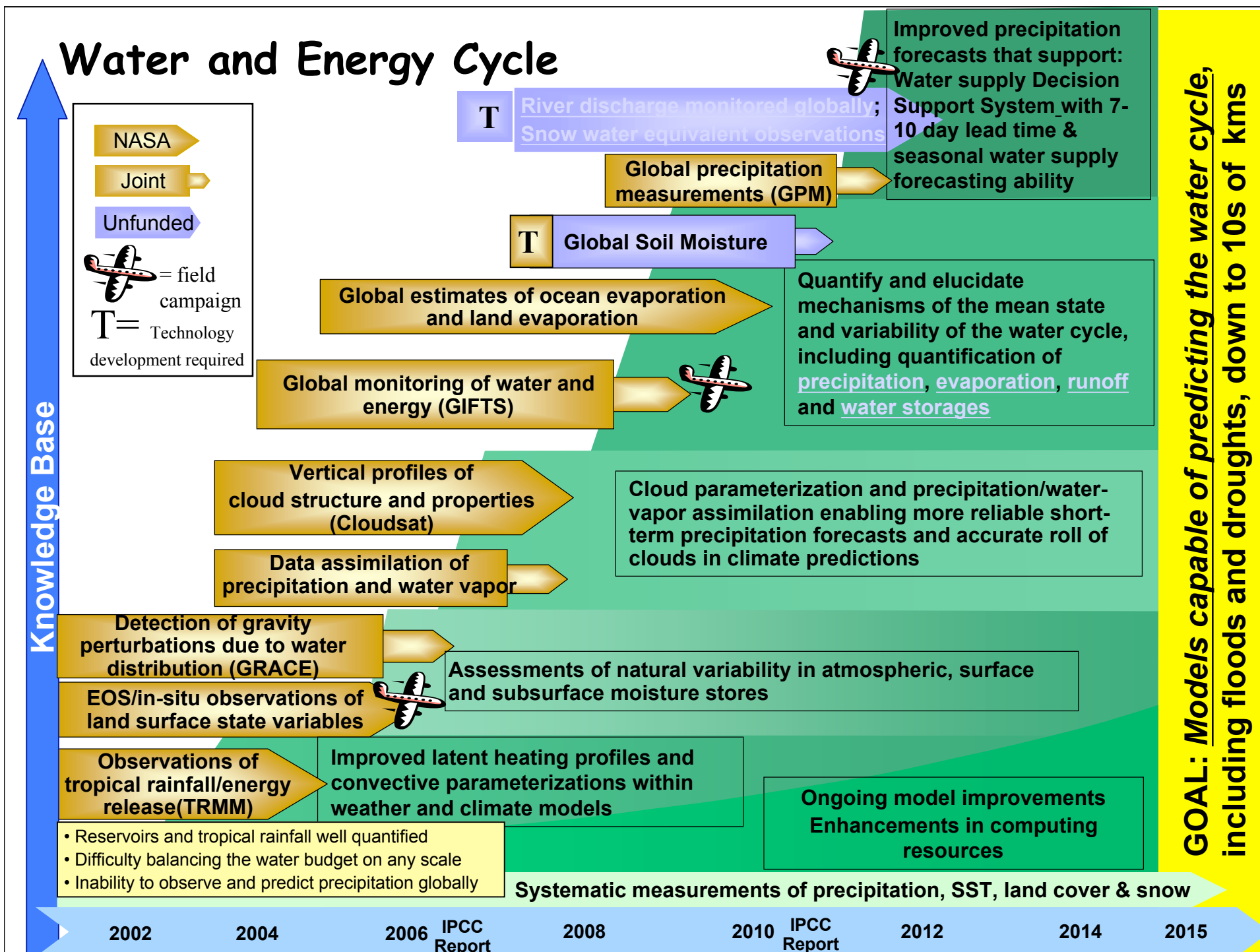
Water storage: Drinking Water, Water for  
Commerce and Energy

Linking Human Activity to Climate Change



NASA has the unique capability to provide global observations of the various components of the water cycle, and then use them to enhance global models and improve predictive capability

# Water and Energy Cycle



**GOAL: Models capable of predicting the water cycle, including floods and droughts, down to 10s of kms**



# Anticipated Progress in Answering the Question

## Where we are now

The water budget is only balanced over global and large temporal scales to within 20%. Locally, there are large uncertainties in some observations and modeled quantities of the water budget

Proxy measurements of land surface quantities (partly based on observations and partly based on models).

Limited coverage of satellite measurements of precipitation. Models have large ranges of seasonal predictions of precipitation.

Uncertainty in causes of variability in the water cycle.

## Where we plan to be

Water budget known at subcontinental and seasonal scales. Manageable errors in relevant quantities at the catchment scale.

Global Observation of Precipitation (over entire diurnal cycle) and important land surface quantities (soil moisture, snow quantity) at mesoscale resolution (order kms).

Higher resolution climate models, with improved cloud resolving models, resulting in “useable” seasonal forecasts of precipitation

Resolution of the water budget’s mean state and variability. Knowledge of the major influences on its variability

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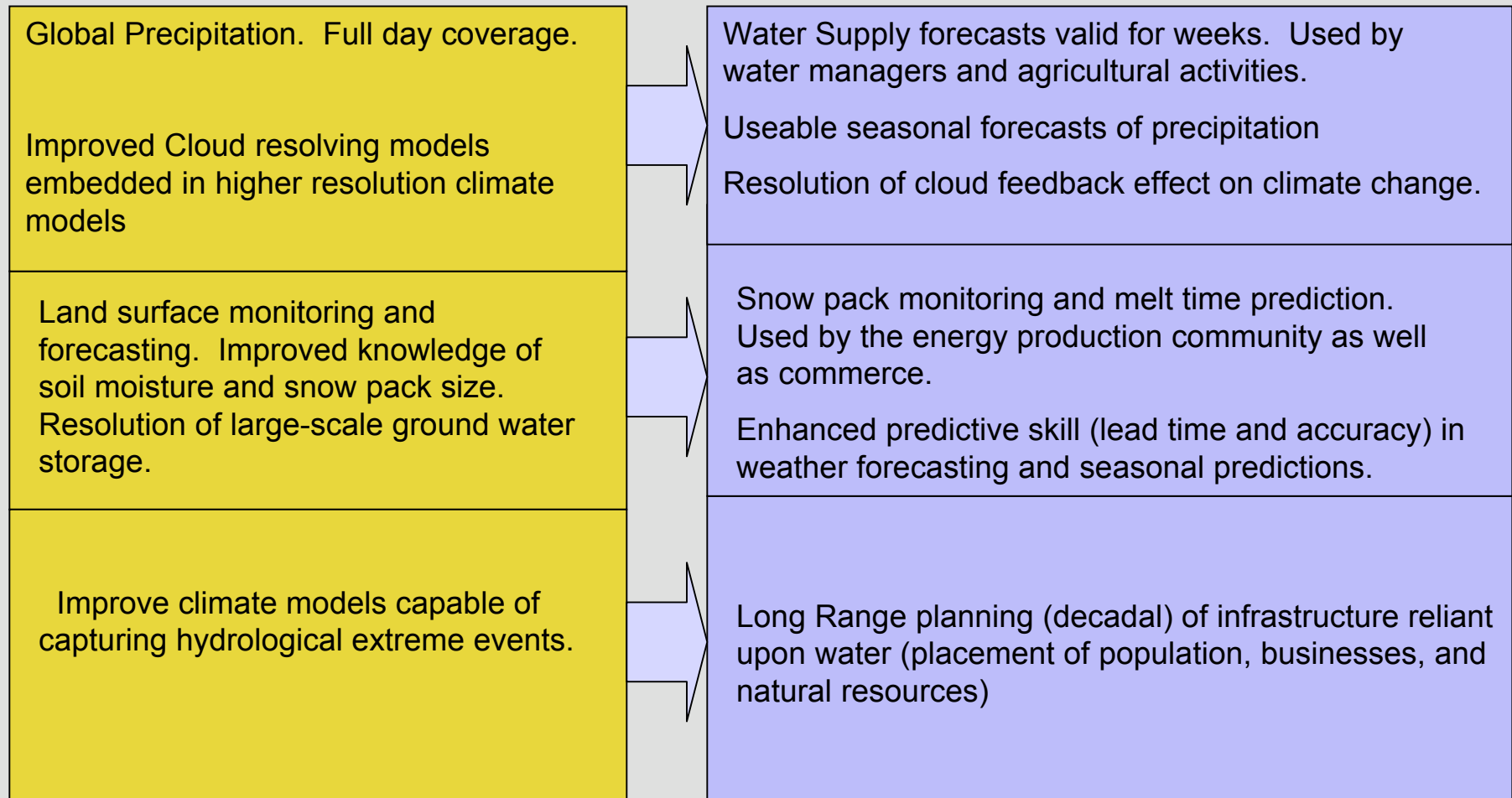


# Anticipated Outcomes of Water Cycle Models

*Improved knowledge of the water cycle and the mechanisms underlying its variability would result in improved estimates of soil moisture, snow pack, storage, river flow, etc.*

## Model/Obs Capability

## Products / Uses for Decision Support

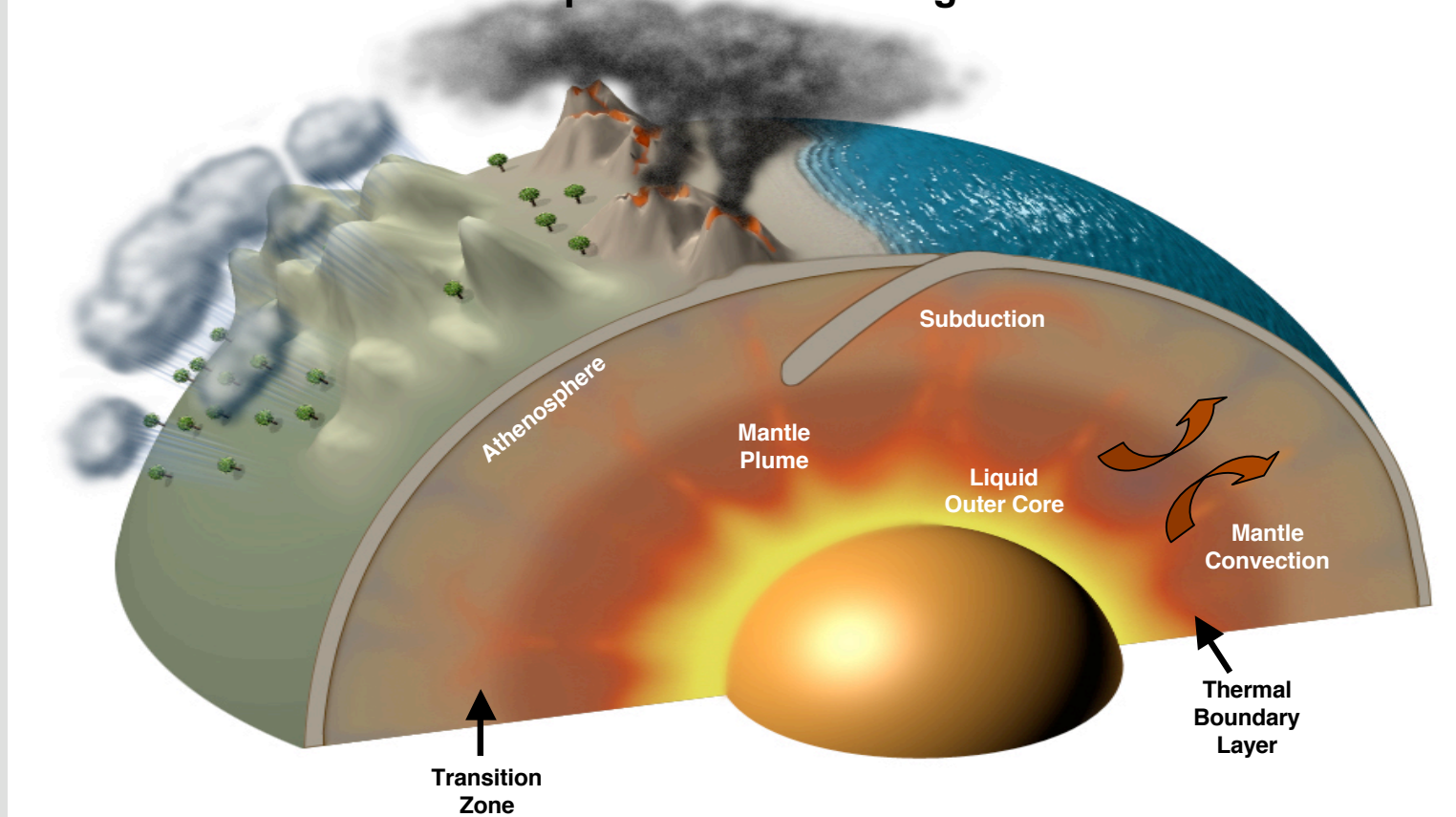




# Earth's Surface and Interior Structure

The Solid Earth Science Working Group (SESWG) has mapped out a course for the future of solid earth research at NASA (<http://solidearth.jpl.nasa.gov>)

How is the Earth's surface being transformed and how can such information be used to predict future changes?



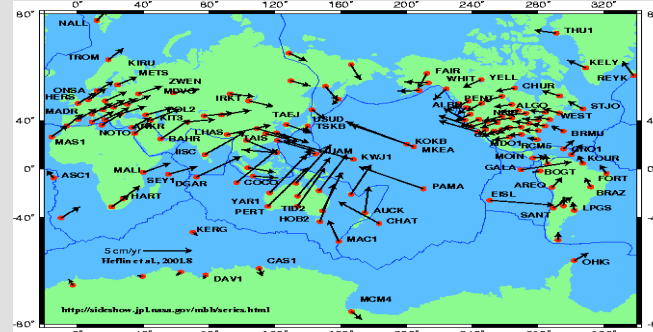
What are the motions of the Earth and the Earth's interior, and what information can be inferred about Earth's internal processes?



# How is the Earth's surface being transformed and How can such information be used to predict future changes?

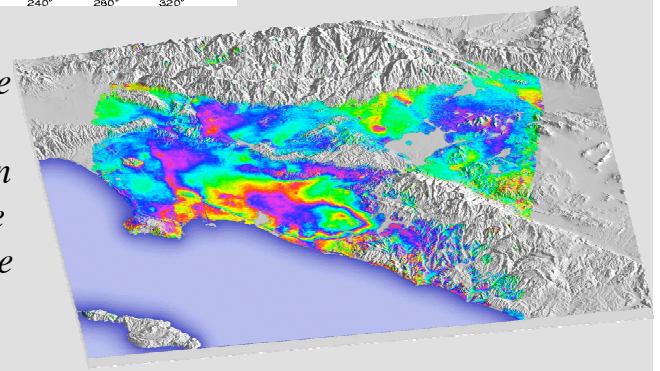
## Background and Issues:

- Natural hazards such as earthquakes, volcanoes, landslides, floods, sea level rise, and wildland fires are major societal threats.
- Characterizing and understanding the underlying forces is required to move toward predictive capabilities.
- Space based geodetic and gravity measurements are revolutionizing our ability to characterize, understand and predict the changes in the Earth's surface which generate natural hazards.



*Tectonic plate motions measured continuously to better than a mm/yr by the global space geodetic networks.....*

*drive deformation at the plate boundaries such as the L.A. Basin. InSAR and the SCIGN GPS network within the basin measure mm scale surface changes due to these tectonic forces and changes in aquifer water content.*



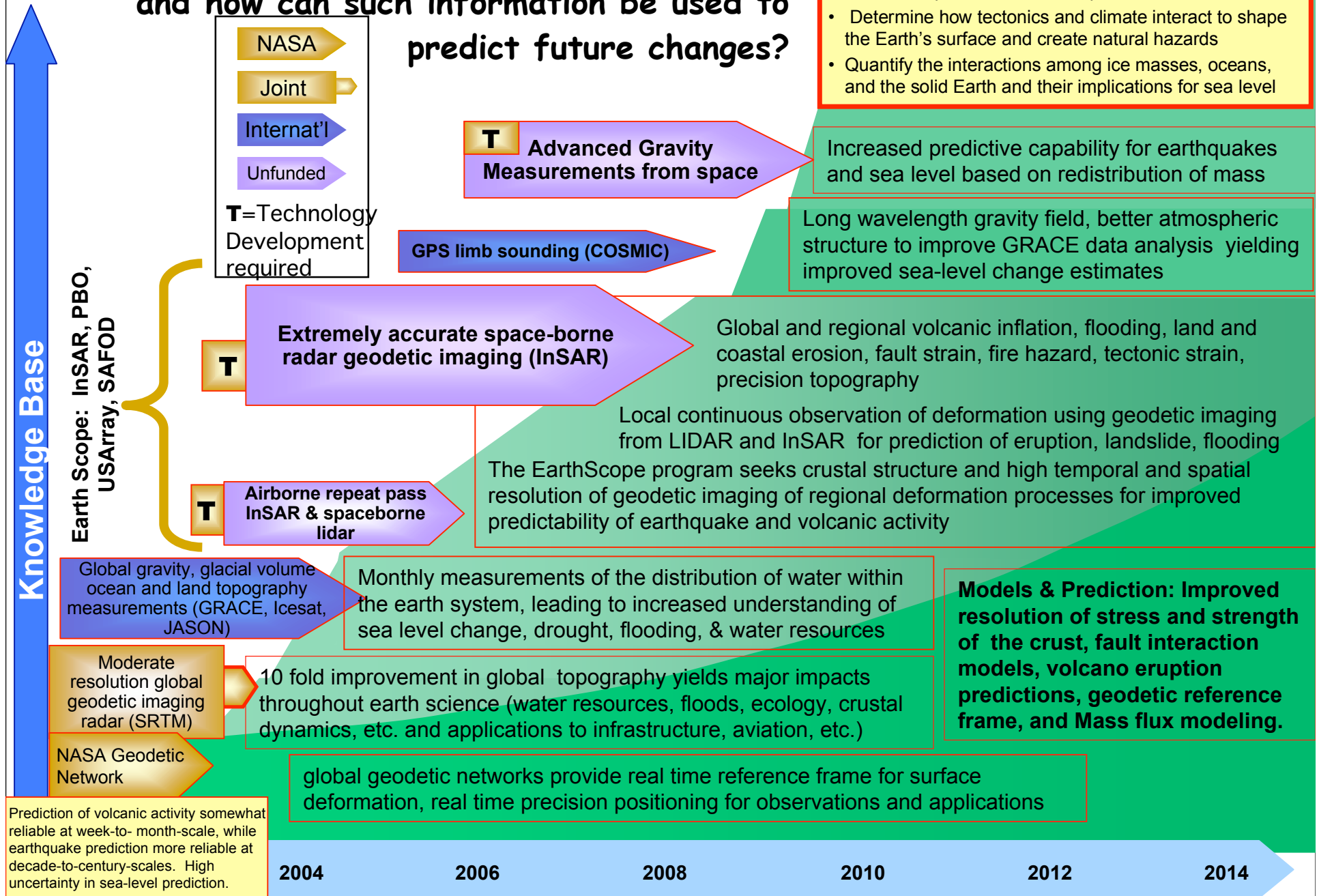
## Why NASA:

NASA sponsored geodetic networks provide a stable accurate reference frame and regional fiducial measurements with mm resolution using NASA developed technology and international collaboration.

NASA developed Interferometric Synthetic Aperture Radar (InSAR) and lidar techniques (both airborne and satellite) provide high resolution topography, surface deformation and surface cover at global and regional and local scales.

NASA provides international leadership and innovation in the development and application of these space geodetic techniques including space based gravity

# How is the Earth's surface being transformed and how can such information be used to predict future changes?





# Progress of knowledge and understanding toward

How is the Earth's surface being transformed and how can such information be used to predict future changes?

## Knowledge Available in 2002

Space geodesy demonstrates measurement of mm scale changes in topography.

Geodetic imaging demonstrated for cm level topography and surface characteristics for fuel load, land and coastal erosion, flooding landslide hazard. Global topography from SRTM at 90m resolution in development

Periodic and aseismic centimeter scale strain events are detected, some seismic precursor events are observed in the surface deformation field.

Volumetric changes in volcanoes detected by InSAR reflect movement of magma at depth without seismic or eruptive manifestations of activity.

Major faults have been identified, post seismic stress changes linked to subsequent earthquake occurrence along some faults.

Landslides can be differentiated by hydrological and seismic forcings.

Time variable gravity due to seasonal atmospheric and hydrologic transport observed at seasonal to interannual scales.

Sea level change estimates of 1-2 mm/yr but mechanism is uncertain and acceleration terms are uncertain.

## Knowledge Available in 2015

Global topography available at meter spatial resolution and decimeter vertical accuracy.

Continuous surface change measurement over key high risk regions at mm scale.

Crustal strain, crustal stress, and crustal strength estimates combined with IT data mining to enable the forecast of earthquakes with annual or better resolution for selected regions.

Volcanic inflation models incorporating geodetic, seismic and optical observations provide up to one year advance warning on eruptive phases for the world's active volcanoes. Global volcano pre-eruptive volcano activity is available to decision makers.

High accuracy and high resolution measurements of time variable gravity detect ocean floor landslides and strain accumulation at ocean trenches and regional water budgets.

Lithospheric loading, mass flux, and reference frame models provide sub mm/yr sealevel change accuracy.



# Progress towards answering question:

How is the Earth's surface being transformed and how can such information be used to predict future changes?

## Products Available in 2002

mm scale Space Geodetic (GPS) point solutions of crustal deformation over selected volcanoes and fault zones.

Two decades of global geodetic measurements, giving mesoscale motion of the Earth's crust at annual rates.

Preliminary 90 meter posting topographic maps for North America and South America. High resolution lidar mapping at 5m postings demonstrated for test sites.

Terrestrial reference frame with 2 to 5 cm accuracy.

Near term volcanic eruption warnings for selected volcanoes, no earthquake or landslide forecasts.

## Products Available in 2015

3-D geodetic imaging of crustal deformation and surface change at high spatial and temporal resolution. GPS and InSAR, hyperspectral imaging supported by lidar mapping in selected

Directed observation of surface change with InSAR and hyperspectral imagery of selected targets for risk assessment and disaster management.

High resolution global topography at meter resolution and decimeter vertical accuracy.

mm scale TRF accuracy and stability on decadal scales for sea level change and regional scale crustal deformation.

Global near and long term eruption risk and alerts, landslide risk assessments for US and selected global regions, severe storm disaster risk models, preliminary earthquake forecasting for selected tectonic zones.